NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

OPERATION
OF AN UNTETHERED,
UNMANNED AIR VEHICLE

by

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September, 1995

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
September, 1995

3. REPORT TYPE AND DATES COVERED
Master's Thesis

4. TITLE AND SUBTITLE
OPERATION OF AN UNTETHERED, UNMANNED AIR VEHICLE

5. FUNDING NUMBERS

6. AUTHOR(S)
Mark G. Hakun

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Postgraduate School
Monterey, CA 93943

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the United States Government.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
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14. SUBJECT TERMS
Archytas, Untethered, Futaba, Repco, Engine Calibration, Pulse Width Modulation, PWM, Digital-to-Analog Converter, DAC, AC100, MATRIXx, SystemBuild

15. NUMBER OF PAGES
74

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

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OPERATION OF AN UNTETHERED, UNMANNED AIR VEHICLE

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Submitted in partial fulfillment

of the requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL

September, 1995

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ABSTRACT

The goal of the Avionics lab at the Naval Postgraduate School is to develop an unmanned air vehicle that can be mass produced frugally with items readily available in the commercial marketplace . The Archytas vehicle under concurrent production and development at the Naval Postgraduate School accomplishes just that. This machine combines computer generated code, personal computer and radio controlled equipment into a small, but capable vehicle with applications in both the military and civilian sectors. In order to achieve flight free of tangible links to the earth's surface, computer models of the system evolved into a series of electrical signals mixed with commands of the ground-based pilot. These signals along with those of the on-board sensors blend inside the controlling software to produce stable flight. The initial phase of flight without the tether was successful in the test cage.

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ACKNOWLEDGMENT

I would like to express my appreciation and thanks to those who supported this thesis. Dr. I. I. Kaminer readily provided his determination, wisdom and direction in perservering on an ambitious project. Dr. R. M. Howard extended his vast insight. Mr. Don Meeks contributed many hours of technical insight and sincere dedication. Lastly, my wife Maurann encouraged me to achieve with overwhelming confidence and sacrifice.

I. INTRODUCTION

A. BACKGROUND

For the better part of the last three years, the Avionics Lab at the Naval Postgraduate School has undertaken the complex task of developing and implementing control systems for Unmanned Air Vehicles (UAVs). Two models in particular have progressed to the point of being capable of flight free of tangible connections to the earth. The first, Bluebird, is a conventional aircraft. The other major project is the Archytas vehicle which has a ducted fan propulsion system. It is inherently unstable and requires constant monitoring of multiple parameters to maintain safe flight even with an experienced pilot.

The focus of this thesis is development of the RF link for feedback control of Archytas. The controller developed earlier sent the Pulse Width Modulated (PWM) signal up the tether directly to the vanes, but the modifications discussed eliminate the hardwired link. [Ref. 1]

The second key element to removing the tether was the application of a modem transmitter to send the Inertial Measurement Data to the AC100 serial module. Kataras discusses this operation in detail [Ref. 2]. The proximity of the test facility to the Monterey Pennisula Airport prohibited complete testing of the downlink, but laboratory testing validated the rapid and accurate transmission of data when the entire vehicle is integrated. Currently, however, the tether functions as power supply and datalink for the Inertial Measurement Unit (IMU). Future testing with a Navy approved frequency will prove the functionality of the complete system.

The electrical system complexity has grown with the removal of the umbilical. A variety of signals were transmitted along the tether, but the unit must now be self-sustaining. An alternator exists for the unit, but it must be rectified and stepped

up or down to provide the different requirements of the on-board avionics. Current technology has produced rechargeable batteries with sufficient currents and minimal weights to be used on Archytas. Since the current version of the vehicle is much lighter than that of the original vehicle, the batteries serve as needed ballast. Later on they will serve as back up power supplies.

The vehicle can be seen in Figure 1.1. As shown it also has reconaissance devices for use once it becomes completely functional and marketable. The vehicle, once piloted and untethered flight has been proven reliable, can be programmed to fly to waypoints and repeat complex flight paths. The viability of a Differential Global Positioning System (DGPS) for the vehicle was proven in Ref 3. All that is required is a second modem transmitter to downlink the position data to the updated controller. [Ref. 3].

B. SAFETY

The current operating system has some flaws that make safety a concern prior to and during flight testing. The current starter presents multiple hazards and is highly inefficient. The fuel vents lack support and can be ingested into the propeller. The electrical supply line for ignition has a large current and must be secured immediately. The unmuffled engine generates a loud noise and requires hearing protection. The craft can be operated safely, but those involved must be properly trained to do so.

C. CONTRIBUTIONS OF THESIS

- Developed SystemBuild code for untethered pilot commands.
- Developed SystemBuild code for untethered computer control.
- Developed AC100 C30 Animation command modules for direct vane commands.

- Performed throttle servo calibration.
- Performed vane position calibrations.
- Computed engine torque correction.
- Developed system operation procedure for Archytas.
- Performed untethered, caged flight tests using direct pilot commands.
- Performed extensive safety evaluation of system.

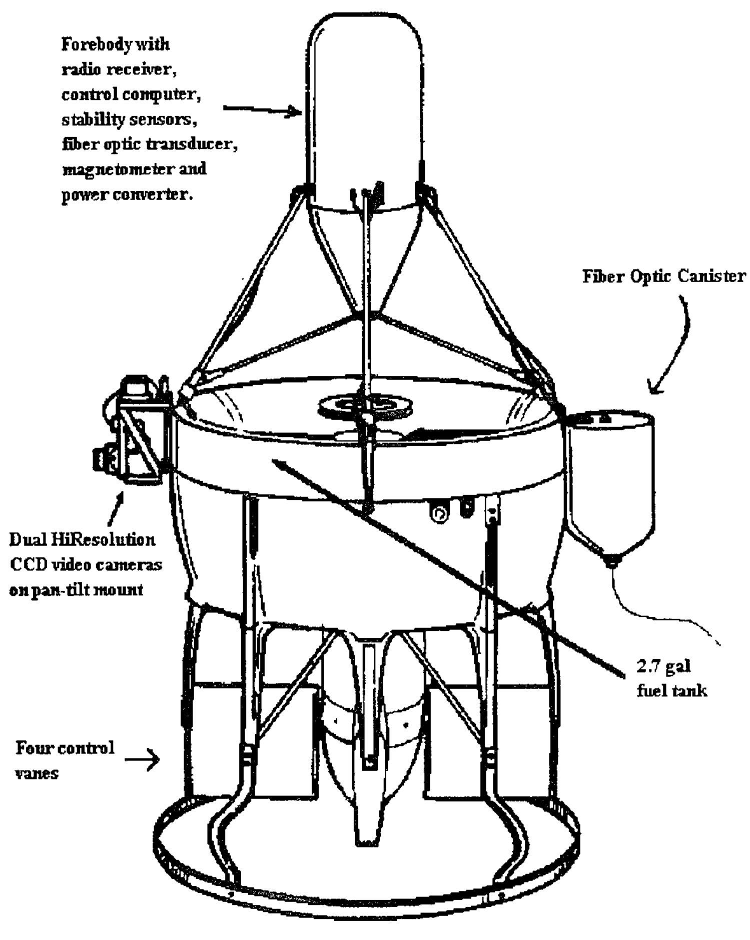


Figure 1.1: Archytas Vehicle [Ref. 4]

II. SYSTEM DESCRIPTION

A. TETHERED VEHICLE

The focus of the previous attempts at creating a stable vehicle centered on tethered flight. All commands and sensor outputs travelled to and from the Integrated Systems AC100 controller through the twenty-four pin tether [Ref. 1]. This umbilical was connected at the base of the vehicle at its centerline. This allowed ease of flight testing by ensuring all signals reached the vehicle without interference. It also permitted hardware-in-the-loop testing of the controller, sensor, and vanes because an identical hardware mockup simulated the aircraft's control surfaces. The throttle could not be simulated, however, since the model did not predict the aerodynamic forces on the vehicle when it is flying with a pitch in translational flight. The umbilical itself has its problems. Since inherent weight of a vehicle limits the payload capacity, any type of tether drastically reduced the range. Each ten foot length of the current electrical tether weighs 2 lbs. Therefore a range of 200 feet would add 40 lbs. which is not possible with the current engine thrust. Any obstacles in the flight path could interfere and sever the tether making any controller on the ground useless and cause the loss of the vehicle. Initial testing gave the throttle control to the ground based pilot operating with a Futaba transmitter. He also had control of the kill switch which commanded a servo to shut off fuel to the engine. The onboard receiver was powered from the umbilical connection. The umbilical connection also supplied the 28 V for the IMU. [Ref. 1]

The original design for maneuvering the vehicle used a crude joystick box directly connected to the wiring harness. Voltage changes generated by the movement of these control sticks were sensed by the analog-to-digital converter (ADC) card and the controller computed the desired vane combinations. A PWM signal was sent up

the umbilical and moved the appropriate vanes. The position of the vanes was then sensed and returned down the tether and read out on the flight display. The vane positions were not used in the controller as referenced positions. [Ref. 1]

Figure 2.1 shows the original hardware testing set-up. The majority of the components are still available for use. The shaded ones are not available. The joystick has been removed in favor of entirely RF vane movements. Commands may still be entered through the AC100 screen, but this is not practical for actual vehicle operations unless a screen display of an actual Futaba transmitter can be generated. Since the Navy license for the RF modem has not been received, the tethered set-up still has utility. Figure 2.2 shows the current pin assignment for the tether. [Ref. 2]

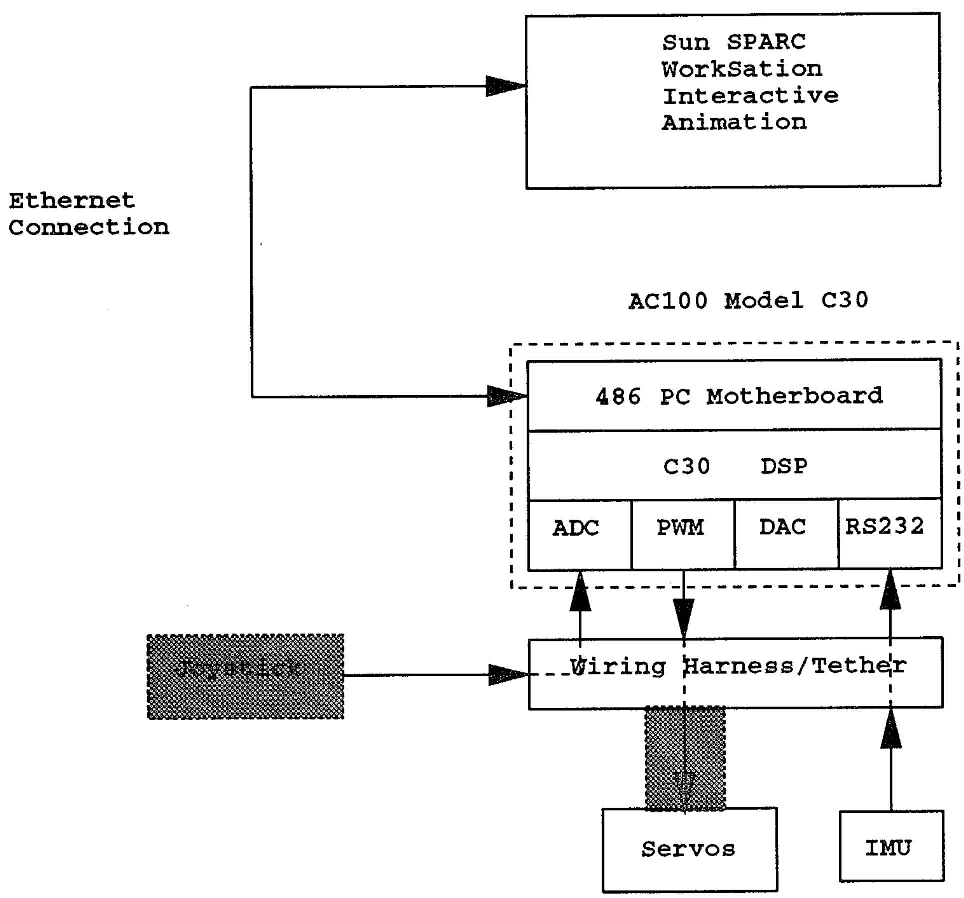


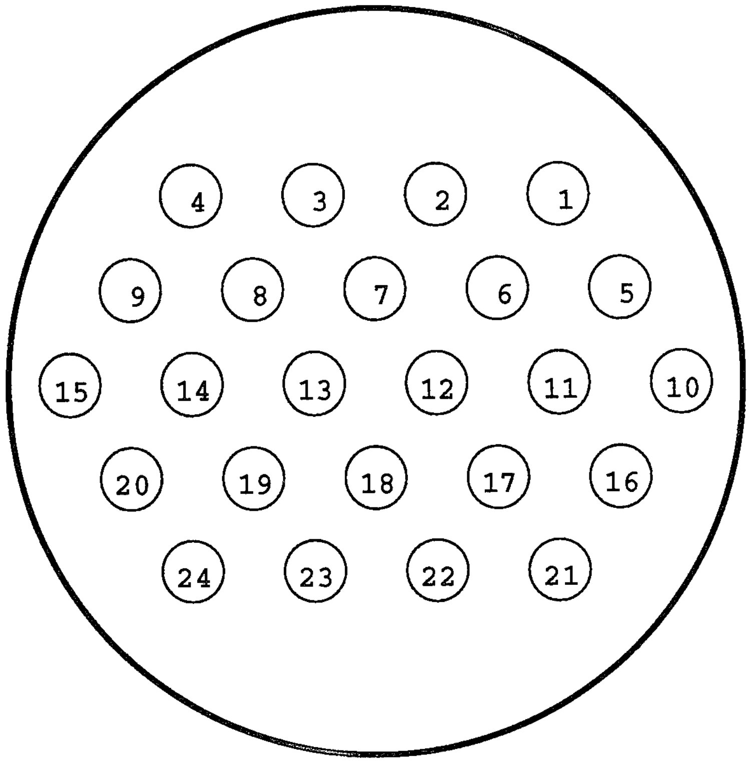
Figure 2.1: Archytas Hardware Setup, Tethered Flight

B. UNTETHERED VEHICLE

To eliminate the umbilical, a way to send the IMU signals to the controller was established using the Repco modem [Ref. 2]. When the DGPS work by Christofis is intergrated, a second identical modem with a different frequency must be installed as well [Ref. 3]. This will allow a flight path to be pre-programmed in the controller. The vehicle will fly to way points in three-dimensional space with the accuracy of the DGPS system. At the current stage of testing only one transmitter can be installed on-board the vehicle. This allows a pilot to maneuver the vehicle within the line of sight. The on-board modem exceeds 1 Watt of transmission power and thus requires frequency authorization, as will a second transmitter. The datalink has proven viable in the laboratory, but requires licensing before actual testing can be performed. Kataras details the operation of the on-board transmitter and ground station receiver; therefore it will not be explained here. [Ref. 2]

Since the vehicle requires directional control, a pilot on the ground has command of the vanes. This is done by linking him with the AC100 system and the vehicle at the same time. One receiver on the aircraft accepts throttle and kill switch commands. The kill switch shuts off fuel to the engine and will eventually employ a safety parachute to allow safe landing if an engine casualty occurs in flight. A second receiver on the ground station receives four commands from the two sticks. The commands were originally designed to be throttle, rudder, elevator and aileron. The nomenclature was changed for inital testing to more closely fit helicopter terminology as will be explained in Chapter IV.

A Futaba transmitter has been modified to generate commands using the AC100 system. Normally, a stick on the Futaba sends out a PWM signal in the range of 900 μsecs to 2100 μsecs depending on its movement. The stick creates this this signal by



Pin Number	Content	Pin Number	Content
1	Not Used	13	IMU Rx
2	Not Used	14	IMU Tx
3	Not Used	15	5 V Return
4	Not Used	16	Not Used
5	Not Used	17	Not Used
6	+24 V Power	18	Not Used
7	24 V Return	19	Not Used
8	Not Used	20	Not Used
9	Not Used	21	Not Used
10	Not Used	22	Not Used
11	+5 V Power	23	Not Used
12	IMU Ground	24	Not Used

Figure 2.2: Modified Connector End of Wiring Harness Tether

reading a voltage created by a variable resistor connected to the stick. The modification involves attaching wires to the voltage sensors inside the transmitter. The AC100 C30 generates the appropriate voltages in the four pre-determined outputs on the digital-to-analog converter card (DAC) module. The Futaba transmitter generates the required PWM signal. Since the transmitter always creates the same pulse width in the outgoing signal with the same respective input voltage, a consistent calibration curve can be established. Due to the modification, physically moving these sticks will not generate any PWM signal to be sent out. The Futaba Digital Proportional Radio Controllers emit less than 1 Watt and do not require licensing. However, care must be taken when using the Futabas on radio controlled fields not to interfere with other radio transmitters. This would have catastrophic effects on the vehicle. Also, because the power emissions are small, range is limited to 1000 meters in altitude or 500 meters along the ground [Ref. 5].

The electrical power requirements for the different transmitters and receivers vary. Each Futaba transmitter has its own battery supply and must be properly charged prior to operation. Normal charge provides at least 1 hour of continued operation. The corresponding receivers require 5 V power supplies and draw no more than 100 mA of current. The two different receivers may be powered from alternate sources depending on the type of operation. If tethered testing is required, the umbilical can supply power. Otherwise, the vehicle has two battery supplies near the respective receivers. The throttle/kill switch receiver is located on the body between vanes 1 and 4. Meanwhile the vane receiver and battery are attached above vane 3. The IMU draws 28 V at less than 300 mA. The umbilical also provides this, but for free flight two 12 V batteries in series provide adequate current. The IMU functions properly with as little as 22 V. The Repco modem requires 12 V and during

flight a rechargeable battery will provide adequate power. The batteries will be placed along the upper ring assembly and serve also as needed ballast in the current configuration. Ultimately, the on-board alternator will be rectified and stepped accordingly to supply each of the sensors placed on board. Table 2.1 delineates current power requirements.

TABLE 2.1: Power Requirements of Individual Components

Component	Voltage	Current	Power
IMU	22-30 V	300 mA	.5 Watts
Repco Transmitter	12 V	300 mA	3.6 Watts
Futaba Receivers with Servos	4.8 V	500 mA	2.4 Watts

The system wiring configuration is depicted in Figure 2.3. The dual Futaba system has been proven in operation to generate vane commands for the Bluebird aircraft up to an altitude of 1500 feet. For Bluebird, instead of controlling individual vanes, the computer commanded control box generated PWM signals for the corresponding control surfaces: rudder, ailerons and elevator. The range limitations observed in the system during flight testing at a radio controlled (RC) aircraft field were in the reception of the pilot generated signal by the ground station receiver. The electromagnetic fields created by the multiple electronic devices destructively interfered with the pilot's commands. This can be corrected by using a dual conversion receiver and stretching out the receiver's antenna to its full length further away from the ground station.

The entire system has gained in simplicity by limiting the number of physical lines needed. Figure 2.4 shows, however, that untethered flight has gained dependence on multiple RF links. All links have been proven to work in the Avionics laboratory, but the complete IMU integration has been delayed by problems with the

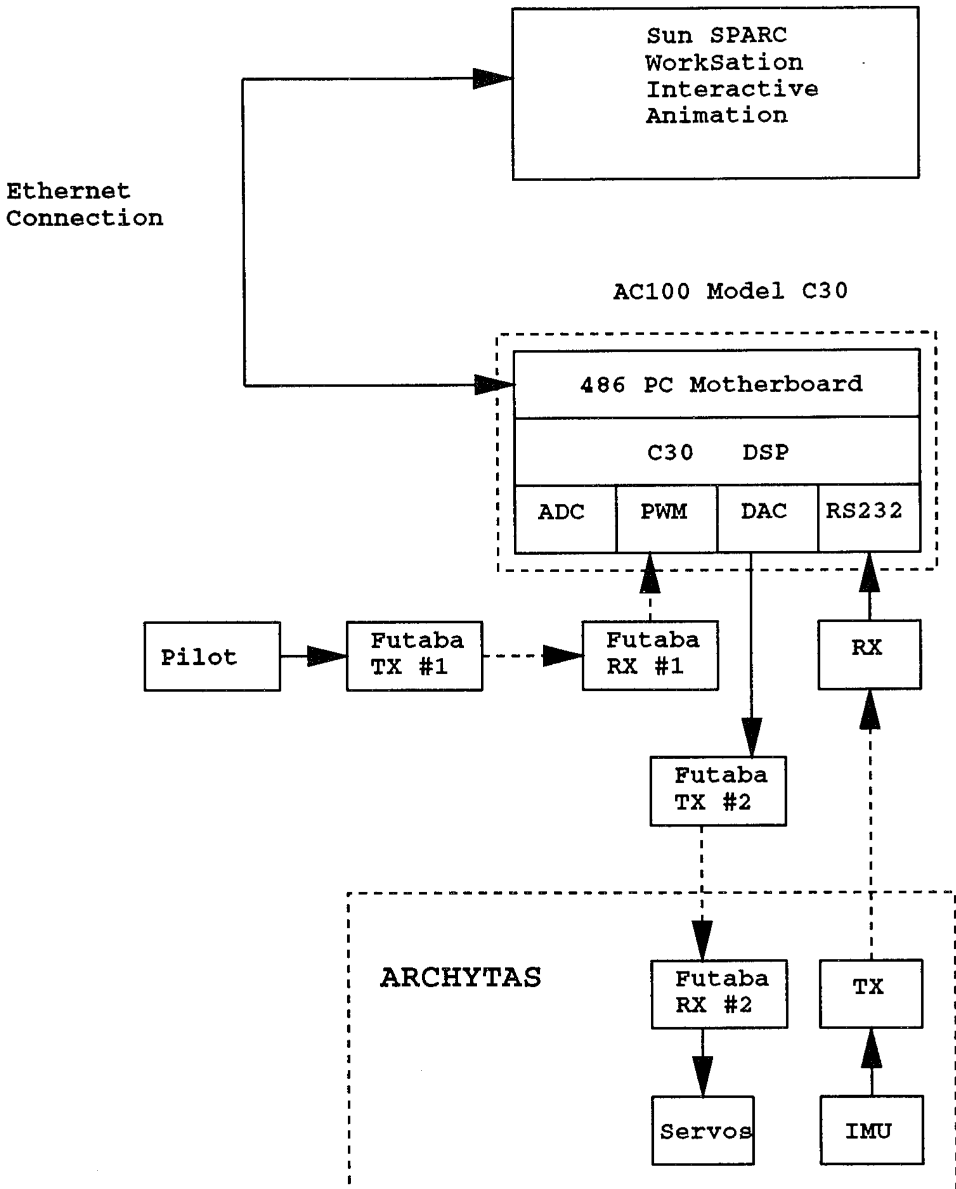


Figure 2.3: Archytas Hardware Setup, Untethered Flight

IMU EEPROM mapping and waiting for Navy frequency approval for the data downlink [Ref. 6].

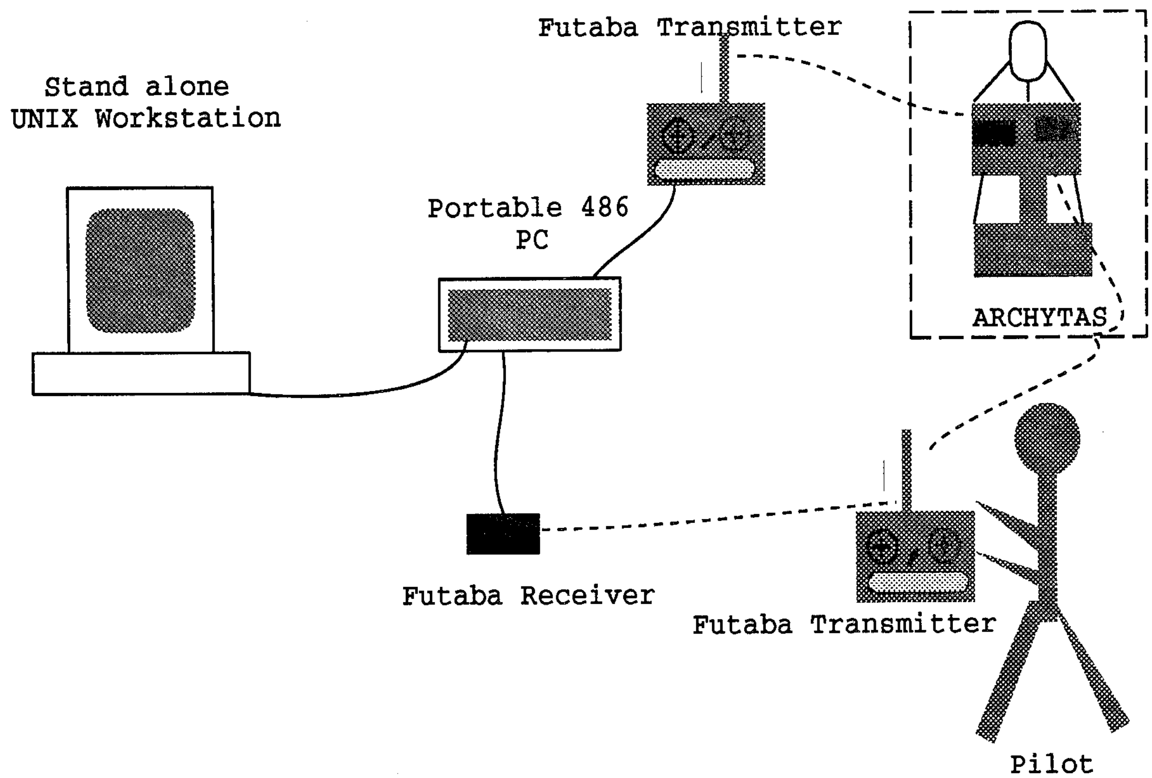


Figure 2.4: New Flight Test Setup

The many changes that have altered the vehicle have also changed its pre-loaded weight in a positive way. Since the IMU used is a commercial off-the-shelf product, the weight of additonal dedicated circuitry is eliminated. Table 2.2 lists the current weight of the air frame and avionics. Flight testing at this stage required ballast just to get the weight up to the controller designed weight of 85 pounds. Engines, such as the one used in Archytas, are designed to run at close to maximum rpm for efficiency and smooth operation. The controller cannot account for the excess thrust and airflow unless it weighs this much.

TABLE 2.2: Weight of Individual Components

Component	Weight	Quantity	Total Weight
Imu	1.92 lb	1	1.92 lb
Repco Transmitter	4.08 lb	1	4.08 lb
Futaba Receiver	0.09 lb	2	0.18 lb
Fuel & Tank	21.00 lb	1	21.00 lb
12 volt batteries	2.56 lb	4	10.24 lb
5 volt batteries	0.20 lb	2	0.40 lb
IMU Pod base	2.29 lb	1	2.29 lb
IMU Pod mid-section	0.56 lb	1	0.56 lb
IMU Pod cover	0.49 lb	1	.49 lb
IMU TX mounting bracket	0.55 lb	1	0.55 lb
Futaba servo	0.23 lb	6	1.38 lb
Engine	14.00 lb	1	14.00 lb
Propeller	2.00 lb	1	2.00 lb
Air Frame	4.00 lb	1	4.00 lb
Duct Skins	2.00 lb	1	2.00 lb
Ballast	5.00 lb	4	20.00 lb
Total Weight			**84.37 lb**

III. FUTABA DIGITAL PROPORTIONAL RADIO CONTROL SYSTEM

The key to untethered, controlled flight is an accurate, reliable wireless transmission of commands to the vehicle's control surfaces. The Futaba digital proportional radio control performs these functions. It produces a PWM signal with consistency. The transmitter creates a signal between 900 μsecs and 2100 μsecs depending on the position of the stick on the box. A typical pilot transmitter is pictured in Figure 3.1 along with the pilot's commands. A similar figure appears in Chapter IV showing the pilot commands required for Archytas. The transmitter used was designed for small scale model aircraft. The generated signal performs a function according to which stick was maneuvered.

A. CHANNEL COORDINATION

Proper coordination between stick, receiver and servo functions is required. All Futaba command functions generate a PWM signal corresponding to a channel on the receiver (see Figure 3.3). The servo or servos that are connected to that port on the receiver operate according to pulse width of the signal generated. Table 3.1 shows the nominal stick function and channel. The throttle stick is notched and remains where its placed without force. The other three sticks return to the center position unless held in place. All sticks have associated trim levers which allow adjustment of the hands off position. [Ref. 5]

TABLE 3.1: Channel Output of Standard Futaba Commands

Function	Channel
CH1	Aileron servo
CH2	Elevator servo
CH3	Throttle servo
CH4	Rudder servo
CH5	Landing gear servo
CH6	Flap servo
CH7	Aux
CH8	Aux
CH9	Aux

B. POWER REQUIREMENTS

The transmitters come with their own rechargeable batteries. Normal charge is 9.6 V and safe operation requires 9.4 V or greater. The units may be charged overnight or quickly charged in 15 minutes. Functional life is approximately one hour.

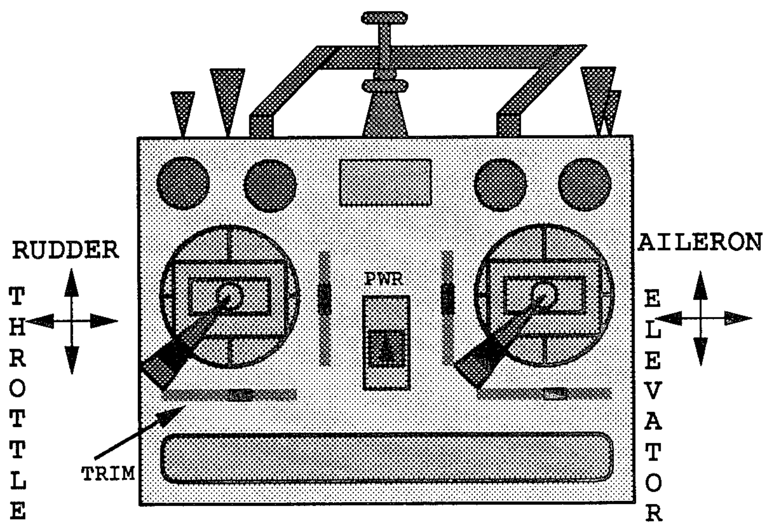


Figure 3.1: Futaba Digital Proportional Radio Controller

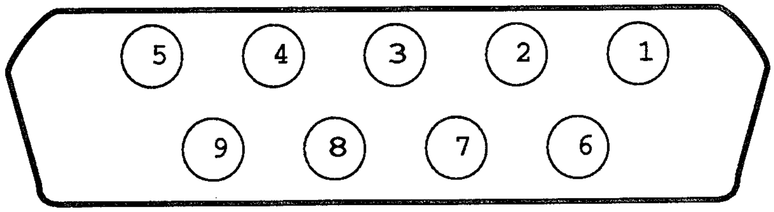
C. FUTABA TRANSMITTERS

The pilot uses a Futaba transmitter similar to the one pictured in Figure 3.1. However, the signals he generates conform to functions explained in the control chapter. The kill switch has been designated on Channel 5.

An RF transmitter is required to command the vanes on Archytas. The AC100 C30 system commands the vanes by using a Futaba transmitter similar to the one that the pilot uses. Voltage changes that are caused by stick movements are simulated by the digital-to-analog output card in the AC100 C30 system. These voltages are applied through a nine-pin male connector to a port created on the side of the Futaba. Figure 3.2 shows the connector and corresponding loads. Outputs for proper servo operations require input voltages in the 1.5 to 3.3 V range, with about 2.3-2.5 V being the stick neutral position. This, of course, depends on the orientation of the actuator in the specific application. For the Archytas vehicle, 2.31 V is required for the 0^o degree position. The vanes are limited to +/- 30^o movement by limiting the voltage applied to the modified transmitter. Using 2.31 V as a neutral position for all four vanes, varying the input voltage -/+ .47 V allows for the desired range of movement on Archytas. The direction and voltage must be consistent during calibration. Table 3.2 shows the voltages required for movement in each vane.

TABLE 3.2: DAC Voltage to Vane Position Correlation

Vane Position	DAC Voltage
-30^o	2.78 V
0^o	2.31 V
30^o	1.84 V



Pin Number	Content
1	DAC #1
2	DAC #2
3	DAC #3
4	DAC #4
5	—
6	10 volt
7	—
8	—
9	Ground

Figure 3.2: Futaba Modifcation Pinout

The four vanes are associated with the output of the DAC module connected to the PC, which generates the voltage input to the ground station Futaba transmitter. Table 3.3 shows the transformation from DAC to vane movement.

TABLE 3.3: DAC to Vane Correlation

DAC Channel	Futaba Channel	Vane
1	1	2
2	2	1
3	3	4
4	4	3

D. FUTABA RECEIVERS

Figure 3.3 shows a representative Futaba dual conversion receiver. As shown in Table 3.1 receivers on Archytas have nine outputs. Older receivers have less, but since only five outputs are connected to any one receiver, they may be used as long as they match the transmitter being used. The dual conversion receiver contains an internal crystal that generates a signal at a different frequency. This filters the signal to prevent noise from corrupting the servo command. Each receiver and transmitter have a matching color coded frequency designation.

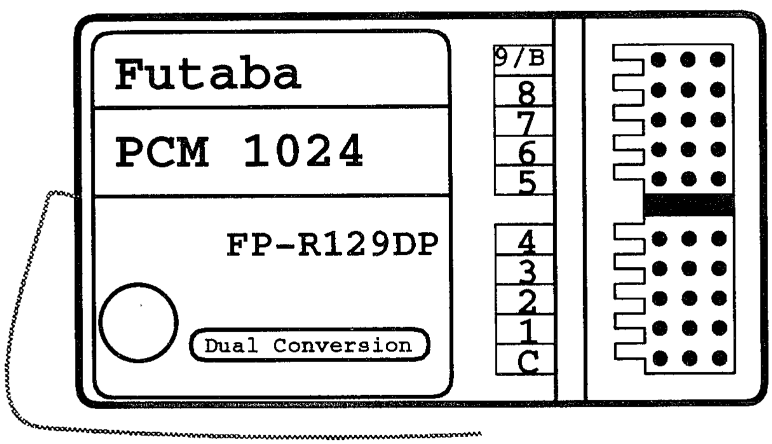


Figure 3.3: Futaba Receiver

The vehicle requires two separate frequency receivers. The throttle signal is sent directly to Archytas, while the pilot command signals must be converted to vane commands and sent on a different frequency to the vehicle. The required pinouts for the receivers are depicted in Chapter V.

The ground station requires a receiver to interpret the pilots commands and translate them into the appropriate vane commands. Engine throttle data is also

required by the controller. Experimentation explained in Chapter IV develops a correspondence between the PWM signal commanded by the pilot and the engine RPM. Table 3.4 shows the correspondence between pilot command signal and channel on the PWM module of the AC100 system. The pilot command nomenclature is delineated in Chapter IV.

TABLE 3.4: Pilot Transmitter to PWM Module Channel Correlation

Pilot Command	Futaba Channel	PWM Module Channel
Fore/Aft Cyclic	2	4-7
Right/Left Cyclic	4	4-11
Rudder	1	4-9
Throttle	3	4-13

E. VEHICLE SERVOS

Moats develops the curves on servo response and generated output response with a PWM signal [Ref. 1]. The PWM signal generation is no longer necessary since the vane commands are generated by their own specific transmitter in the required PWM format. The engine throttle servo is connected to Channel 3 of the pilot's Futaba and the kill switch is associated with Channel 5.

IV. CONTROL ASPECTS

A. NOMENCLATURE

The controller for Archytas uses a body coordinate frame relative to that of a conventional aircraft. The Y_{BODY} axis runs out vane 2. The Z_{BODY} axis runs out vane 1. The X_{BODY} axis is aligned with the thrust axis. This differs from the convention is Kataras because of improper replacement after servo modifications [Ref. 2]. Figure 4.1 shows the body coordinate frame of the vehicle with vanes numbered for identification. Table 4.1 lists the vane combination convention and Figure 4.2 shows the convention for positive vane movement is in a clockwise direction. These terms lose meaning, however, to the pilot on the ground trying to fly the vehicle at a 90 degree angle of attack or pitch. Elevator still affects pitch, but if the vehicle orientation has changed since liftoff due to roll, he may require yaw instead. Moving any two opposing vanes will change the nose-up flight profile. To eliminate the uncertainty for the pilot, a helicopter nomenclature has been adapted for using the Futaba control transmitter.

TABLE 4.1: Vane Deflection Combinations for Positive Angles

Surface	Angle	Vane Combination
Aileron	Roll,Φ	$V_1 + V_2 + V_3 + V_4$
Elevator	Pitch,Θ	$V_2 - V_4$
Rudder	Yaw,Ψ	$V_1 - V_3$

As shown in Figure 4.1, the conventional coordinate system is still used. The commands on the Futaba system have been adjusted to use helicopter terminology. The left stick on the Futaba control transmitter serves as the throttle and rudder. The rudder in this type of operation serves to rotate the vehicle around the X_B-axis as the conventional aileron would. The right stick functions as the Forward/Aft Cyclic and Right/Left Cyclic. Pushing the sticks in the corresponding positions should move

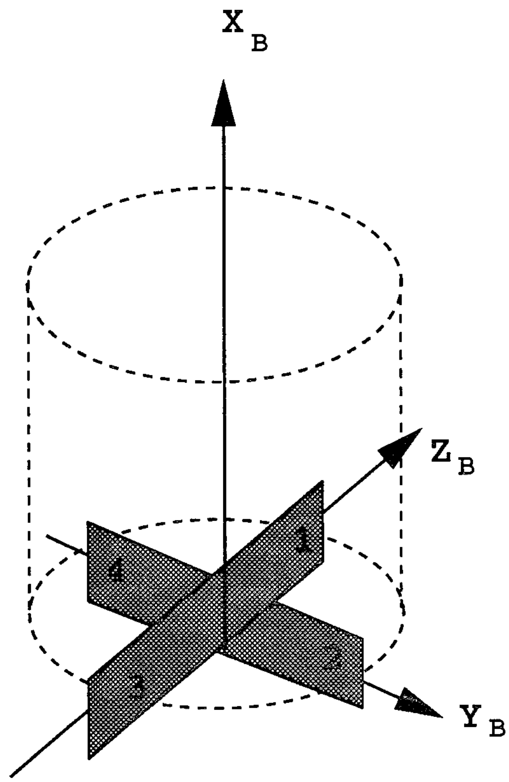


Figure 4.1: Body Coordinate Frame of Archytas

the aircraft forward (away) from the pilot or aft (toward) the pilot. Placing the stick right or left should move the aircraft in the corresponding direction relative to the pilot. Figure 4.3 displays a representative Futaba transmitter.

Sandia Laboratories wind tunnel tests showed that the maximum amount of pitch to be allowed is +/- 10^o ($80^o - 100^o$) [Ref. 4]. This corresponds to a ten mile per hour vehicle velocity [Ref. 4]. In the current configuration throttle must be adjusted by the pilot to maintain thrust equal to the weight of the aircraft. At a 10^o tilt engine thrust must be increased by 1.5% to compensate for the loss in altitude.

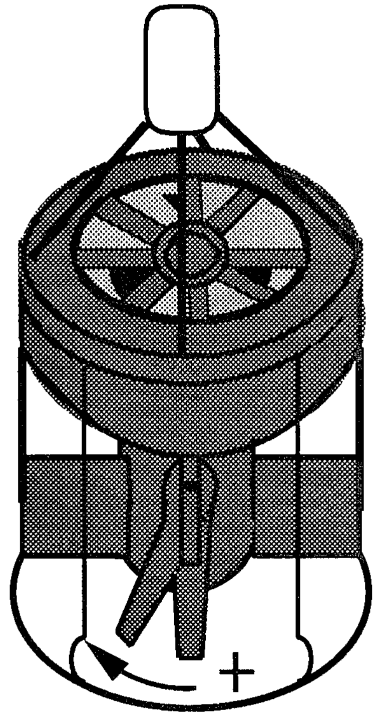


Figure 4.2: Convention for Positive Vane Deflection

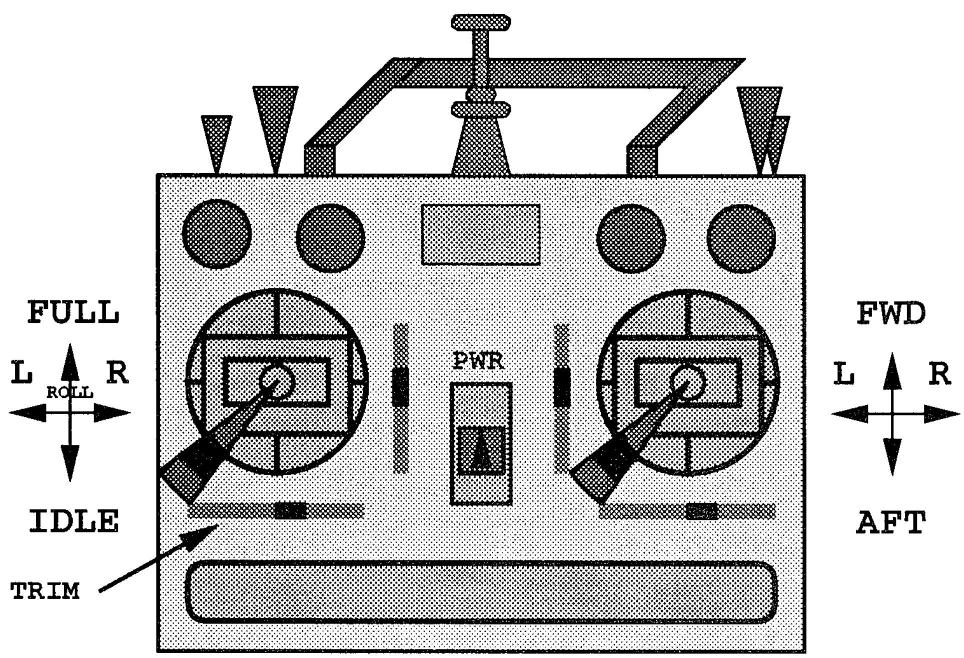


Figure 4.3: Futaba Controller Commands

A correspondence between the pilot's desired vehicle orientation/movement and the controller inputs must be implemented to properly maneuver the vehicle. There are infinite aspects that the pilot may have in relation to the vehicle. Figure 4.4 shows that as long as the pilot's field of view looks directly down on vane 1 will a pitch increase move the vehicle forward. This can be the case only a small percentage of the time. Otherwise, the natural reaction of the ground based pilot to move the craft away from him will pitch the vehicle in an undesirable direction. To overcome this conflict means the contoller must sense when the needed control input should be reflected in a different vane combination or combination of vanes. The angle Ψ is sensed by the IMU. This angle is a magnetic compass reading and changes when vehicle orientation relative to the pilot changes. Hallberg has developed a way to account for this in Bluebird [Ref. 7]. It also compensates for the local position of the vehicle relative to the pilot.

B. OPERATION WITHOUT THE CONTROLLER

As Kuechemeister observed, the two cycle engine produces a negative moment around the X_{BODY}-axis of the vehicle. Flow straighteners designed into the construction of Archytas only partially compensate for this effect [Ref. 8]. In order to produce lift with no rotation, a feedback controller is necessary. For engine testing without the IMU, this torque must be accounted for.

The first comprehensive engine data was determined by Stoney. Figure 4.5 and Figure 4.6 plot the thrust and moment for the engine as functions of rpm. Equation 4.1 and Equation 4.2 list the formulas. Figure 4.7 displays the total thrust compsensation required of the ailerons, while Figure 4.8 shows the deflection needed per vane. The average deflection, as computed, varies less than one degree over the optimal flight envelope. [Ref. 9]

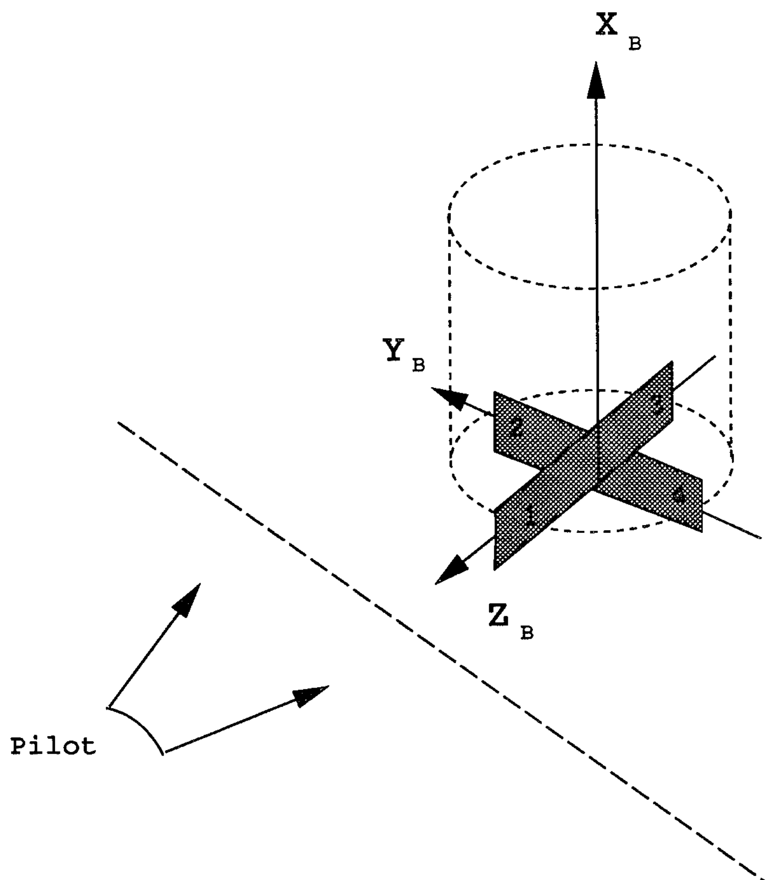


Figure 4.4: Pilot's Line of Sight with Uncorrected Command Inputs

$$thrust(lb_f) = 0.0297rpm - 104.7 \tag{4.1}$$

$$moment(ft - lb_f) = .0542thrust - 0.914 \tag{4.2}$$

The Archytas vehicle in free flight does not have the capability to sense engine rpm. Therefore, data was necessary to calibrate the PWM signal generated by the pilot's Futaba transmitter with the actual engine rpm to make use of the torque compensation mentioned above or as an input to the controller. An engine run up was performed with the vehicle bolted down to its wire mesh transporter. The pilot controlled the engine rpm by cycling his Futaba tranmitter's throttle through its full range multiple times. Standard positions such as idle, half and the full power positions of the throttle were detected by the optical sensor attached to the vehicle at vane 4. The sensor is a Futaba device that produces a relative rpm on an independent Futaba transmitter's screen. The detector has an accuracy of +/- 100 rpm, and its reading must be divided by three for each propeller and multiplied by two because the sensor is calibrated for a two-bladed propeller [Ref. 5]. Maximum achieved engine output was only 7400 rpm, not 8000 rpm. It may be possible to achieve 8000 rpm in rapid forward flight when engine is unloaded by movement of air over blading. Figure 4.9 displays the engine data fitted to a cubic spline curve shown in Equation 4.3.

$$RPM = -7.4832\times10^{-6}(PWM^3)+2.5418\times10^{-2}(PWM^2)-30.411(PWM)+1.9909\times10^4 \tag{4.3}$$

This experimentation was needed to compute the relationship between pulse width generated by the pilot command transmitter and engine rpm. Cycling the

servo from open to closed was used to obtain the torque compensation:

$$\delta_{vane} = -2.6048\times10^{-11}(RPM^3)+5.6512\times10^{-7}(RPM^2)-4.1779\times10^{-3}(RPM)-13.003, \tag{4.4}$$

where δ_{vane} denotes the vane deflection.

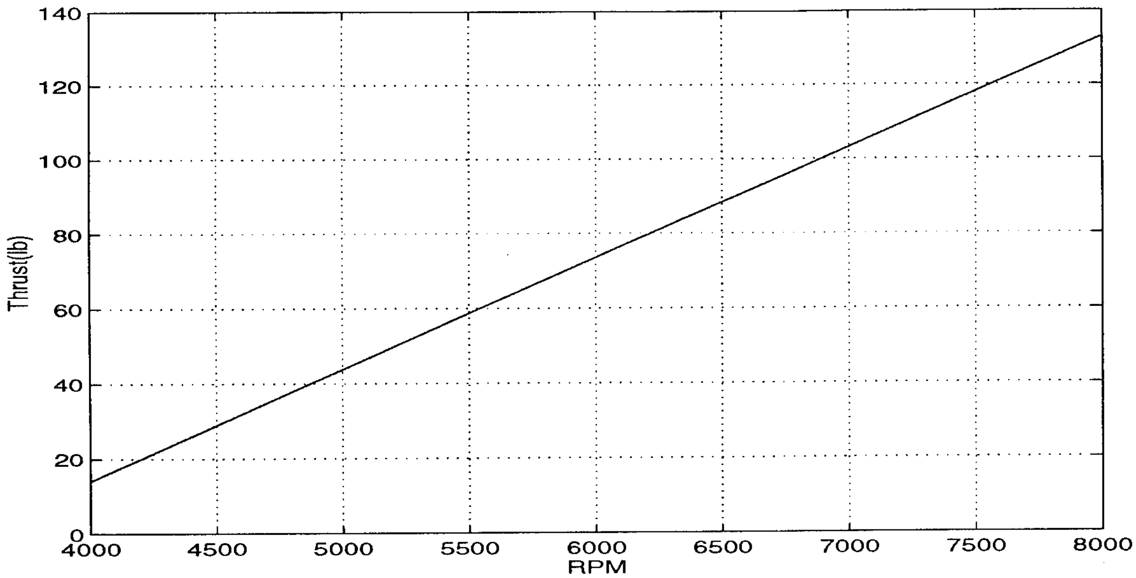


Figure 4.5: RPM vs Thrust

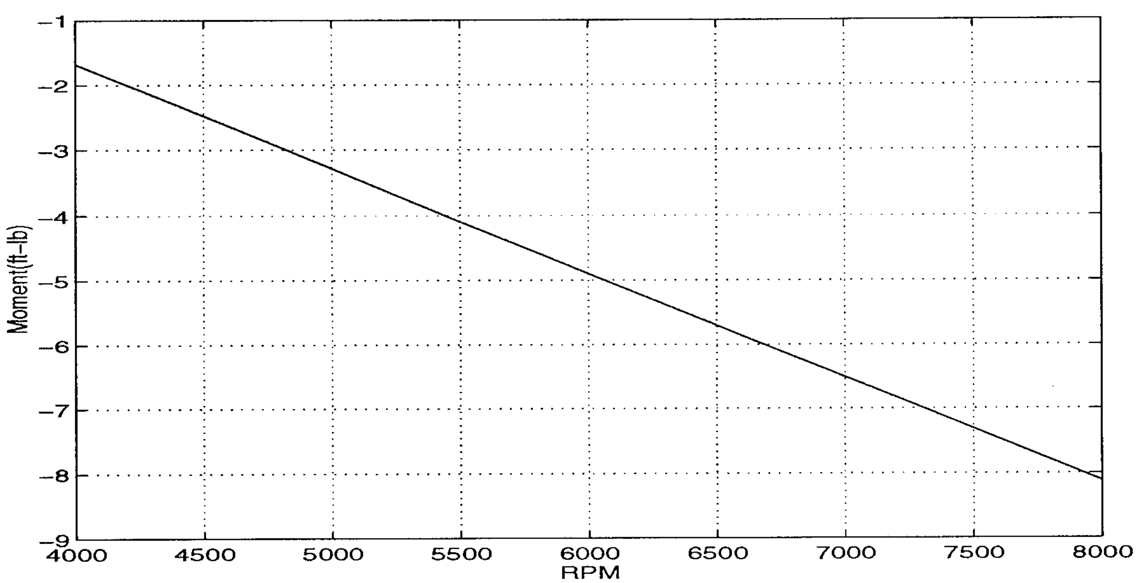


Figure 4.6: RPM vs Moment

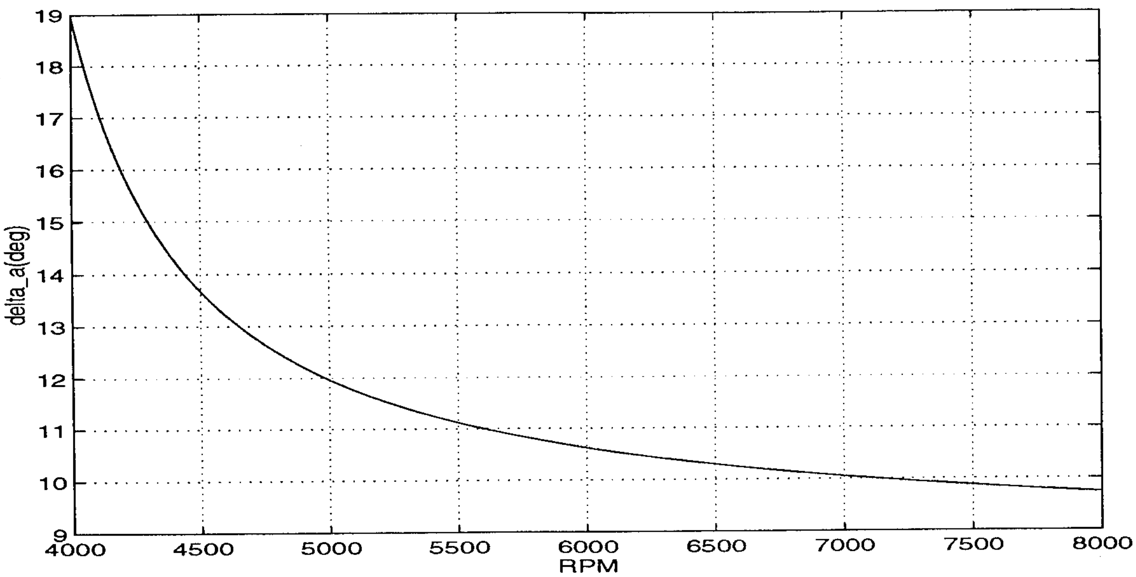


Figure 4.7: Aileron Torque Compensation

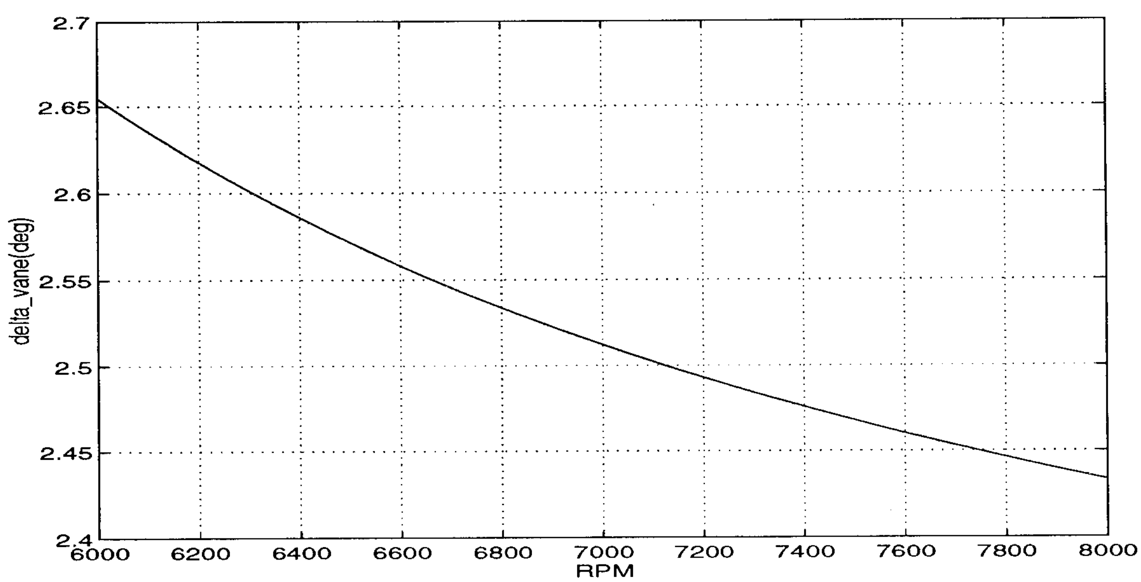


Figure 4.8: Torque Compensation per Vane

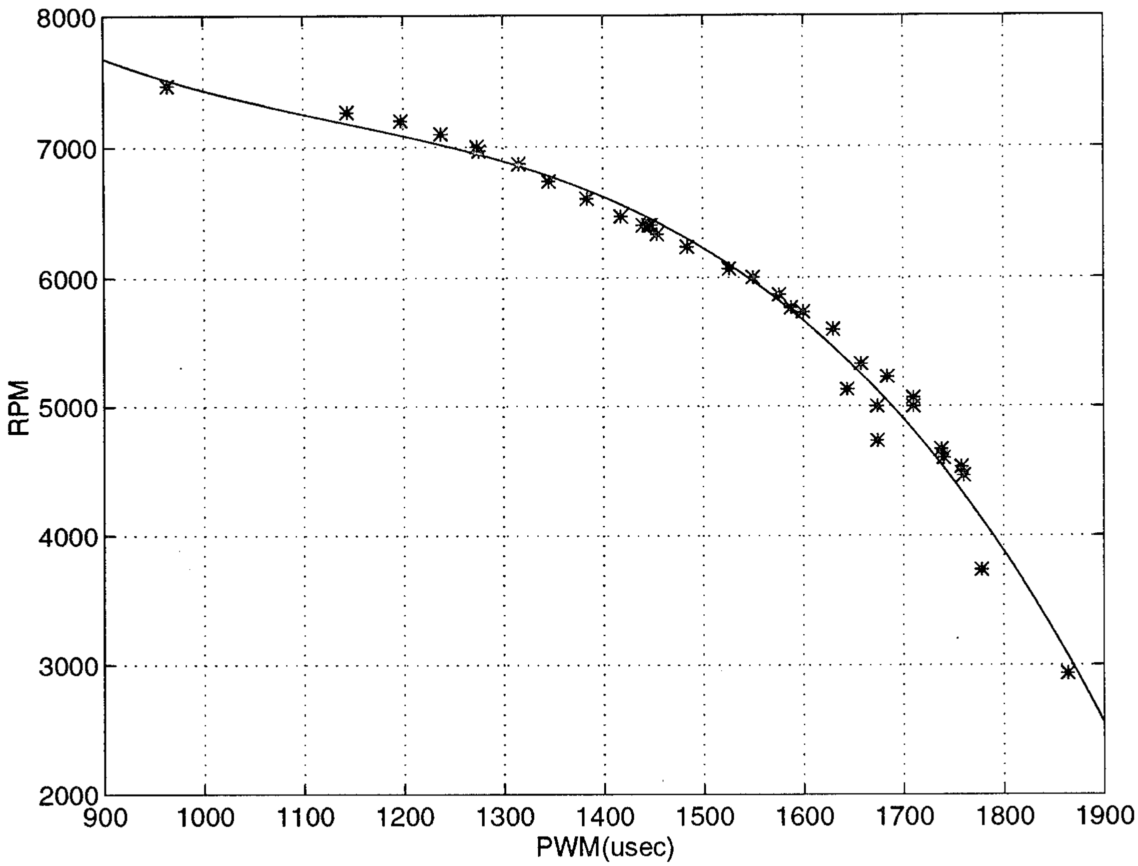


Figure 4.9: PWM vs RPM

V. SYSTEM OPERATION

A. PRE-FLIGHT CHECKS

The sections below outline how to properly prepare the Archytas system for operation. A start-up check-off sheet is included in Appendix A for reproduction and use during all test and operational flights.

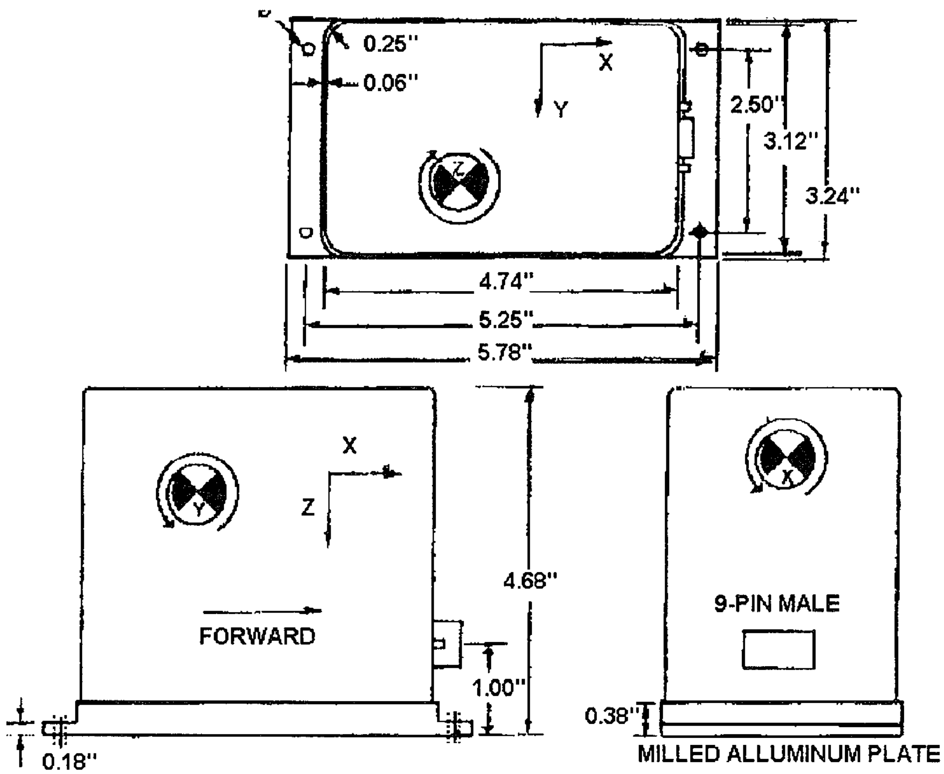
The electrical system on board Archytas supplies power to the IMU, the transmitter, the receiver for the vanes, and the receiver for the throttle and kill switch. Currently, for ease of testing, the engine alternator has not been adapted to supply power for these devices. Rechargeable batteries of various capacities supply it. The IMU and its transmitter use larger 12 V batteries [Ref. 6]. The IMU requires 28 V, but its specifications permit as low as 22 V; therefore two 12 V batteries in series supply adequate power until the alternator adaptations are functional.

All five batteries must be fully charged before light-off to ensure adequate power for all controls. The 5 V batteries can be charged quickly in 15 minutes. The 12 V batteries need an overnight charge. For testing the vehicle in the cage the tether can supply the 28 V for the IMU and 5 V for the throttle/kill switch receiver. The propulsion system for the Archytas consists of a two-cylinder, two-stroke, 290 cm^3 (17.4 in^3) Dynad gasoline engine. The engine is rated for 22 hp at 8000 rpm. Fuel is supplied through the set of four bladders and its common feed line. Total capacity is 2.7 gallons which is enough for 1 hour of operation at 8000 rpm. A full tank should be used for any engine operation to eliminate sloshing effects on an empty tank. Before starting, the engine should be primed twice. The vehicle lacks a battery for the initial spark generation; therefore, a current supply is plugged into the connection between vanes 1 and 4. The current starting device consists of a rope pulled out from flywheel. Care must be taken not to have the end of the pull-starter get caught by the IMU

pod stand or sucked into the blades. This can be done by wrapping the line around the flywheel only once, rather than using the entire length of the rope. In the future, a ratcheting sprocket adapter should be custom manufactured for easier and safer starting. It is common to need multiple tugs on the starter. The combination of the crude starting mechanism and difficulty in light-off make this system suspect and marginally safe at best. Adequate engine warm-up time before any flight operations is five minutes. [Ref. 4]

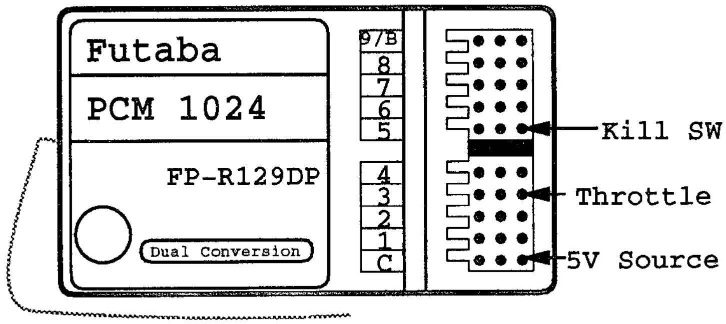
For the control vanes, ensure the battery above vane 3 is connected properly and turn on the switch. The primary sensor on board is the Inertial Measurement Unit produced by Watson Industries of Eau Claire, WI. The IMU is mounted in a four-legged pod that is fastened to brackets on the upper shroud of the vehicle. The brackets are directly above each vane. The inertial axes of the IMU are displayed in Figure 5.1. The inertial X-axis coincides with vane 3. The nine pin connection wire for the down link of the IMU data is connected to the vehicle above vane 3, but the pod's connector is out vane 2. This connection wire needs to be lengthened or elongated. Kataras explains how the Repco transmitter connector is adapted for the IMU. [Ref. 2]

Kataras explains the set-up of the Repco IMU transmitter in detail. Once the internal dip switches are set, they should not be moved. The Repco receiver is identical to the transmitter with the exception of two dip switches. The system has three Futaba receivers. Their pinouts are shown Figure 5.2. They must be connected to their 5 V, 100 mA batteries and switches turned on. The receiver at the ground station does not have a switch. The frequencies of the Throttle/Kill Switch and Ground Station receivers have the same frequency, and must differ from that of the vanes. The operator should pay attention to the polarity of the connectors.

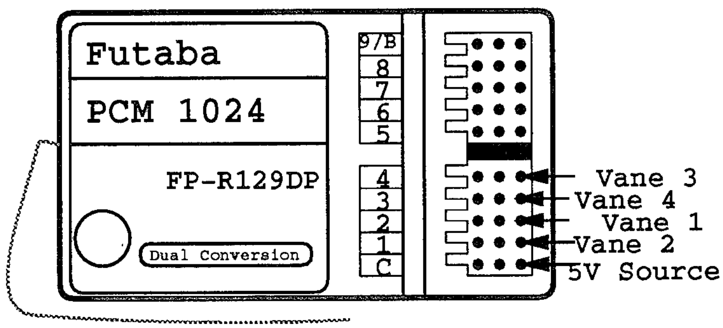


Pin Number	Connection
1	Power Ground
2	+/- 90°
3	Signal Ground
4	-
5	Rx (from user)
6	-
7	Altimeter Input
8	-
9	Tx (to user)

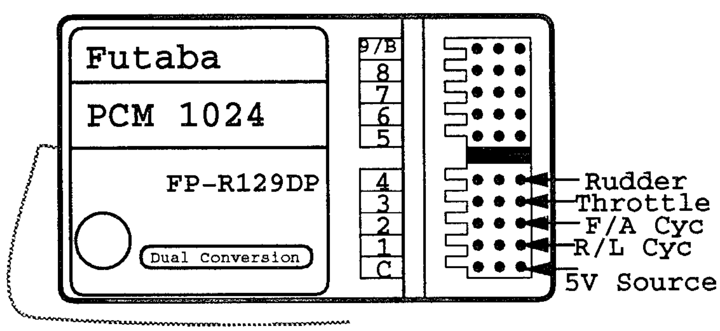
Figure 5.1: Watson Inertial Measurement Unit



Throttle/ Kill SW



Vanes Receiver



Ground Station

Figure 5.2: Futaba Receiver Pinouts

The ground station consists of two computers, their power supply, a Futaba transmitter hardwired to provide vane commands, a Repco receiver and the pilot's transmitter. Instructions to assemble the ground station follow. A proper shaded area must be chosen. The computers do not operate well in intense heat or sunlight. The monitors are also difficult to read even in shaded areas. Ensuring all displays use bold type helps combat this deficiency.

The entire system requires either one outlet or a portable generator that can supply 30 amps. An outdoor extension cord of 50 feet is adequate to keep the generator far away from the ground station and limit noise. A power strip with a surge protector and six outlets attaches to the extension cord and is turned on after all the loads are connected. Table 5.1 lists the electrical loads and power requirements. The harness assembly box is required if the tether is used, otherwise a 12 V battery is required for the Repco modem.

TABLE 5.1: Electrical Loads of the Ground Station

Component	Current
AC100 Computer	10.0 amps
SPARC Monitor	3.0 amps
SPARC Main Hard Drive	4.0 amps
SPARC Aux Hard Drive	2.0 amps
Ignition Power Supply (28 V)	<.5 amps
Harness Assembly (if used for all loads)	9.1 amps

The UNIX system is comprised of three components: Monitor, Main Hard Drive and Auxiliary Hard Drive. All connection points are shown in Figure 5.3. The current stand-alone workstation is identified as 'Intrepid'. The back of the different SPARC stations may vary slightly in configuration. After the wiring is complete, turn on the Auxiliary Hard Drive, Monitor, Main Hard Drive in this order. The switch positions

also vary from station to station as well. The current hard drive and aux hard drive 'ON' positions are reversed from one another.

After the system has completely booted up, log on and select the desired directory. At '>login:', type 'user'. At '>password:', type 'archytas'.

One of two personal computers (PCs) are used: AC100 or America. Ensure all the hardware modules are connected to the correct port on the PC. After connecting the ethernet cable to the common port with the UNIX station, turn on the computer. When the '>C' appears, type 'ac100svr'.

The pilot's Futaba transmitter must be fully charged to 9.6 V before operation. As stated in Chapter II, it can operate with a charge as low as 9.4 V. It may be trickle charged overnight or quick-charged in 15 minutes. The vane command transmitter must be charged like the pilot's Futaba transmitter. Also the male, nine-pin connector must be plugged into the female connector on the left side. The pinout of the connector is shown in Figure 3.2. [Ref. 5]

If the tether is to be used for IMU testing, connect the tether to the base of the vehicle. After the IMU is connected to its on-board link, turn on the wiring harness box.

B. SYSTEM OPERATION

Once the hardware has been set up and preflight tested, the software use takes over the operation. Moats has fully developed the instructions for AC100 system. It will not be explained further here. The current stage of flight testing has its own UNIX project in developmental stages. [Ref. 1]

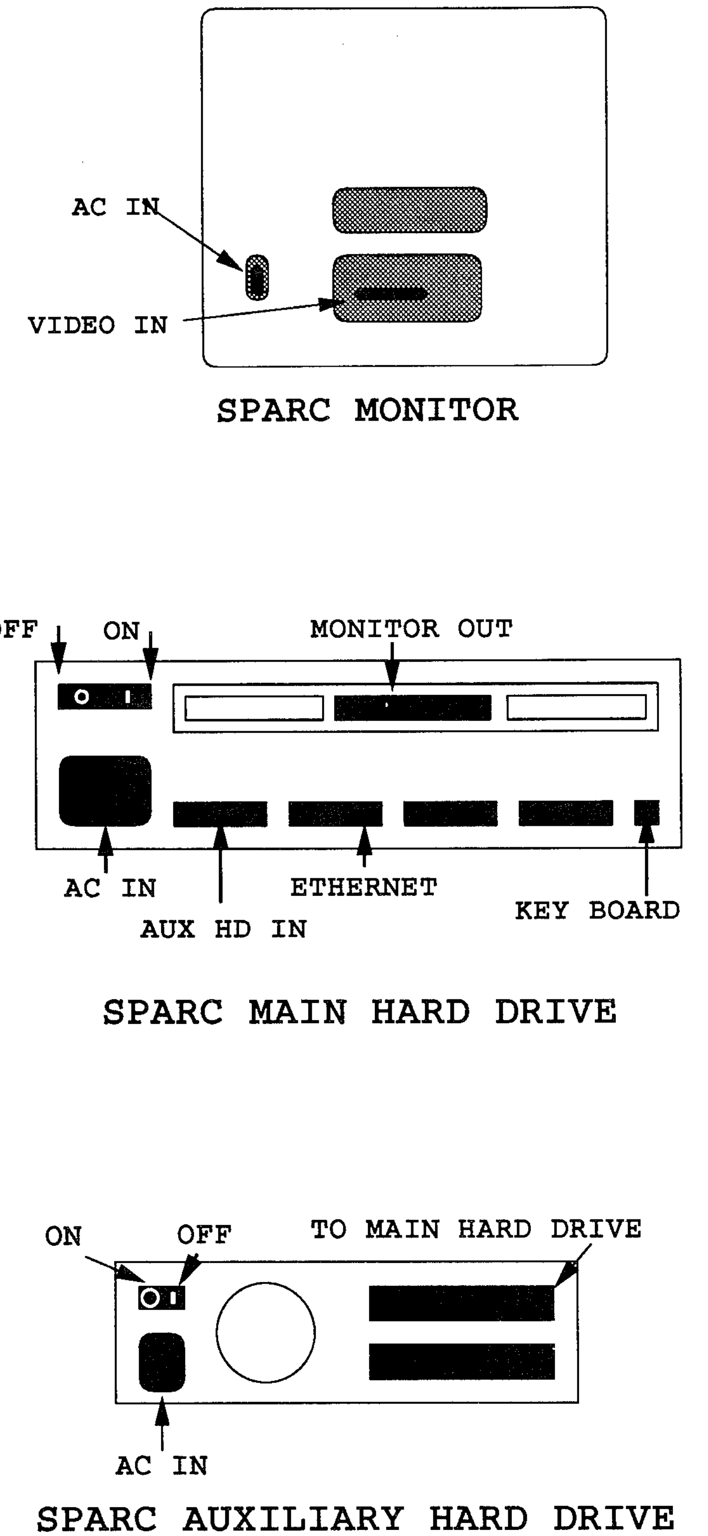


Figure 5.3: UNIX Station Connections, Rear View

C. POST-FLIGHT SHUTDOWN

Turn off the power supplies to both receivers on the vehicle. Disconnect the batteries for the IMU and Repco transmitter.

Drain fuel from the system unless the system is restarted soon that day.

Turn off the control vanes receiver. Disconnect 5 V battery and charge if necessary. Disconnect the IMU from its RS-232 link. This will also disconnect the power supply.

Disconnect the transmitter from battery.

Turn off both Futaba receivers on board.

The computer must be secured properly before it is turned off and power secured. Reboot the controller. Logout. At '>login:', type 'shutdown'. At '>password:', type 'shutmedown'. At '#', type 'halt'. At '>', turn off all three compontents.

Turn off the PC after controller has been rebooted.

SECURE THE COMPUTERS FIRST. Turn off the power strip. Disconnect the battery from the Ground Station Futaba receiver.

Recharge vane command transmitter and pilot control transmitter if necessary.

Disconnect the tether from the base of Archytas. Turn off wiring the harness and unplug the harness form power strip.

VI. SAFETY ISSUES

A. IGNITION SYSTEM

The current engine ignition system presents hazards to the persons starting the machine. The flywheel mechanism requires numerous pulls to cause ignition. Each time the rope is pulled from around the flywheel it has the possibilities of either getting caught by the IMU pod mounting or being sucked into the propellers. Only those experienced at starting the vehicle are aware of these dangers. The engine requires an electric, ratcheted system that can be started with a push of a button or turn of a key.

During the original Sandia testing phase a 12 V DC motor was adapted for use as a portable starter. Two prongs on the starter shaft engage mating slots in the center of the propeller hub. Upon engine start-up, the engine overspeed drives the prongs out of the slots and allows the starter motor to be lifted away from the engine. [Ref. 4]

The pilot must be independent of the flight crew starting the vehicle. He has control of the 'kill switch' which will shut down the engine by closing the fuel supply valve. He also has a fire extinguisher nearby.

B. FUEL SYSTEM

Each of the four fuel bladders require venting. The vents are currently half-inch stubs protruding from the body at three of the four IMU pod struts as seen in Figure 6.1. The vents extend upward by attached tubing, but can be sucked into the engine due to the low pressure region above the engine. One vent system can be

constructed using longer tubing that would be interconnected, but not susceptible to being drawn into the propeller . The ends attached to the shroud need clamps to hold them in place.

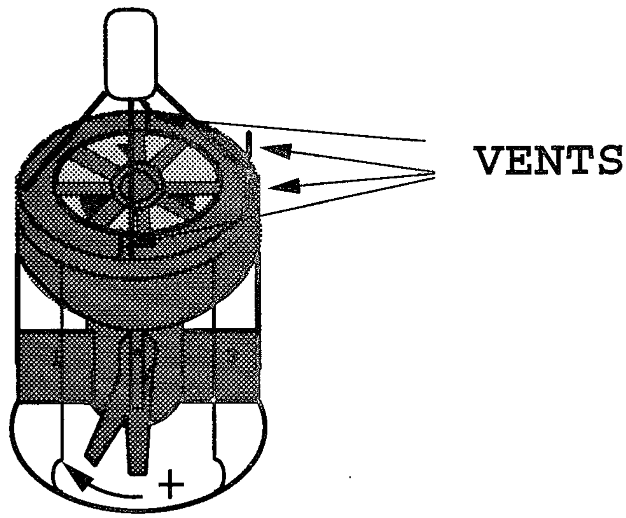


Figure 6.1: Vent Locations

C. ELECTRICAL SYSTEM

The majority of the electrical system is low votage and low current. However, the power supply that is attached between vanes 1 and 4 required for the initial spark puts out a large current supply upon light off. The cord is in the path of the person starting the vehicle and could become a tripping hazard as well. Upon ignition the cord supply must be shut off and removed promptly to prevent any shock hazard to the personnel.

The kill switch, because of its importance to safety, must tested before ignition. This includes fully charging the battery required for its associated receiver.

D. NOISE

The Archytas engine creates a great deal of noise. At one time a muffler system was contemplated for the engine to attempt to reduce the 120 decibels it currently produces. Once the equipment was installed it was not found to significantly or adequately reduce the noise output. Therefore whenever the engine is run all involved in the testing should be required to wear adequate hearing protection. The test facility or flight range used should not be near any high traffic or populated areas.

VII. RESULTS, CONCLUSIONS AND RECOMMENDATIONS

A. FLIGHT TEST RESULTS

Two major phases of flight testing have been satisfactorily achieved for Archytas. First, an engine calibration test allowed determination of the engine output without an on-board sensor. The ground station receiver can sense the pilot's throttle command and convert that into the engine rpm and thrust needed as an inputs to future models. Secondly, operation without a tether proved free flight is possible. The vanes have the desired effects when operating in a restrained flight regime and should operate with great agility when unimpeded. The vane chattering witnessed during tethered flight has no effect on the control surfaces.

B. CONCLUSIONS

The Futaba Digital Proportional Radio Control system has proven to be an effective and adequate data and command link for untethered operation within line-of-sight operation. The Bluebird aircraft flew great distances with signals commanded by the AC100 system controller. Archytas can be commanded the same way with excellent results. The IMU datalink has been proven to operate in the laboratory, but needs long range testing. The IMU EEPROM map has proven susceptible to programming corruption and degradation. This must be corrected for long endurance testing.

C. RECOMMENATIONS

The next step in testing is to integrate the IMU and the controller with the rest of the hardware. Bluebird should be tested first with the datalink since it is inherently stable and can be returned to base without the system in case of malfunctions. The

starting unit for Archytas is suspect and must be replaced with a more suitable and effecient electric device.

APPENDIX A: START UP CHECK-OFF LISTS

TABLE A.1: Vehicle Start-up Check-off List

VEHICLE

[ ] . . . . . .Charge IMU batteries.
[ ] . . . . . .Charge transmitter battery.
[ ] . . . . . .Charge vane receiver battery.
[ ] . . . . . .Charge throttle receiver battery
[ ] . . . . . .Bolt on IMU pod.
[ ] . . . . . .Connect IMU power supply.
[ ] . . . . . .Verify Repco transmitter switch line-up.[Ref. 2] [Ref. 5]
[ ] . . . . . .Connect IMU to Repco transmitter via RS-232 serial link (optional).[Ref. 2]
[ ] . . . . . .Remove vehicle from cart and secure in test facility.[Ref. 8]
[ ] . . . . . .Gas up vehicle.
[ ] . . . . . .Ensure vent lines secure.
[ ] . . . . . .Inspect vehicle for fuel leaks [Ref. 6].
[ ] . . . . . .Inspect propeller blading for nicks and cracks; feel under blade root for spallin Check for tip clearance and lift tips to compare deflection. Rap propeller with screwdriver handle and listen for uniform acoustic response.[Ref. 6]
[ ] . . . . . .Inspect air filters for cleanliness [Ref. 6].
[ ] . . . . . .Inspect hoses and cabling for security [Ref. 6].
[ ] . . . . . .Inspect support struts and forebody for security [Ref. 6].
[ ] . . . . . .Ensure freedom of movement for control vanes [Ref. 6].
[ ] . . . . . .Connect tether to base of vehicle.
[ ] . . . . . .Turn on throttle receiver.
[ ] . . . . . .Turn on vane receiver.
[ ] . . . . . .Connect ignition power supply.

TABLE A.2: Ground Station Start-up Check-off List

GROUND STATION

[ ] . . . . . .Charge Pilot's Futaba transmitter.[Ref. 4]
[ ] . . . . . .Charge Vane Command Futaba transmitter.[Ref. 4]
[ ] . . . . . .Charge battery for Repco receiver.
[ ] . . . . . .Verify Repco receiver switch line-up.[Ref. 2] [Ref. 5]
[ ] . . . . . .Charge Ground Station receiver.
[ ] . . . . . .Connect Ethernet to 'AC100' or 'America'.
[ ] . . . . . .Connect Ethernet to back of SPARC Main Hard Drive.
[ ] . . . . . .Connect 50 foot extension cord to portable generator or wall socket.
[ ] . . . . . .Plug surge protected power strip to extension cord.
[ ] . . . . . .Plug 'AC100' or 'America' in to power strip.
[ ] . . . . . .Plug wiring harness into power strip (optional).
[ ] . . . . . .Plug SPARC monitor into power strip.
[ ] . . . . . .Plug SPARC Main Hard Drive into power strip.
[ ] . . . . . .Plug SPARC Aux Hard Drive into power strip.
[ ] . . . . . .Plug ignition power supply into power strip.
[ ] . . . . . .Start portable electric generator (optional).
[ ] . . . . . .Turn on power strip.
[ ] . . . . . .Turn on 'AC100' or 'America'.
[ ] . . . . . .Once PC has booted up, type 'ac100svr' at the '>'.
[ ] . . . . . .Turn on SPARC Aux Hard Drive .
[ ] . . . . . .Turn on SPARC monitor .
[ ] . . . . . .Turn on SPARC Main Hard Drive.
[ ] . . . . . .Turn on wiring harness (optional).
[ ] . . . . . .Connect battery to Ground Station receiver.
[ ] . . . . . .Turn on Pilot's Futaba transmitter.
[ ] . . . . . .Turn on Vane Command Futaba transmitter.

TABLE A.3: AC100 Start-up Check-off List

[ ] . . . . . .Ensure proper pre-flight brief has been held.
[ ] . . . . . .At 'login:' on SPARC, type 'user'.
[ ] . . . . . .At 'password:' type 'archytas'.
[ ] . . . . . .Change to proper directory on SPARC.
[ ] . . . . . .Type 'C30'.
[ ] . . . . . .Type 'ac100'.
[ ] . . . . . .Compile and link. (Conditional on changes to system).
[ ] . . . . . .Download and run.
[ ] . . . . . .Start controller.
[ ] . . . . . .Calibrate Pilot Futaba.
[ ] . . . . . .Calibrate vane position voltage.
[ ] . . . . . .Check IMU calibration.
[ ] . . . . . .Ensure all members have hearing protection.
[ ] . . . . . .Ensure fire extinguisher charged and ready.
[ ] . . . . . .Start Engine.

APPENDIX B: MATRIX$_X$ — SystemBuild BLOCK DIAGRAMS

The following SuperBlocks are contained in the SystemBuild project for the Archytas Remote Piloting System, currently named ‘hardware’. This project aligns the pilot with the vane 4-2 axis only.

Calibrate_RF_Uplink: Figure A.6 shows the blocks that convert from degrees to voltages sent out to the Ground Station Futaba by the DAC module.

Command_switch: Figure A.4 depicts the SuperBlock that either allows command directly from the monitor or PWM commands. PWM may be entered through the monitor as well.

Command_transmitter: Figure A.3 contains the blocks that convert the pilot or monitor PWM input to directional commands.

Hardware: Figure A.1 shows the upper level project block that takes the inputs and outputs listed in the ‘hardware.rtf’ file.

Process_1: Figure A.2 presents the high level SuperBlock that accepts command inputs from either the monitor or pilot Futaba and computes voltages for the required vane movement commanded by the Ground Station Futaba.

Surface_to_Vane: Figure A.5 depicts the SuperBlock that computes the amount of vane movement commanded by the pilot. It also allows the operator to add or omit the engine torque compensation

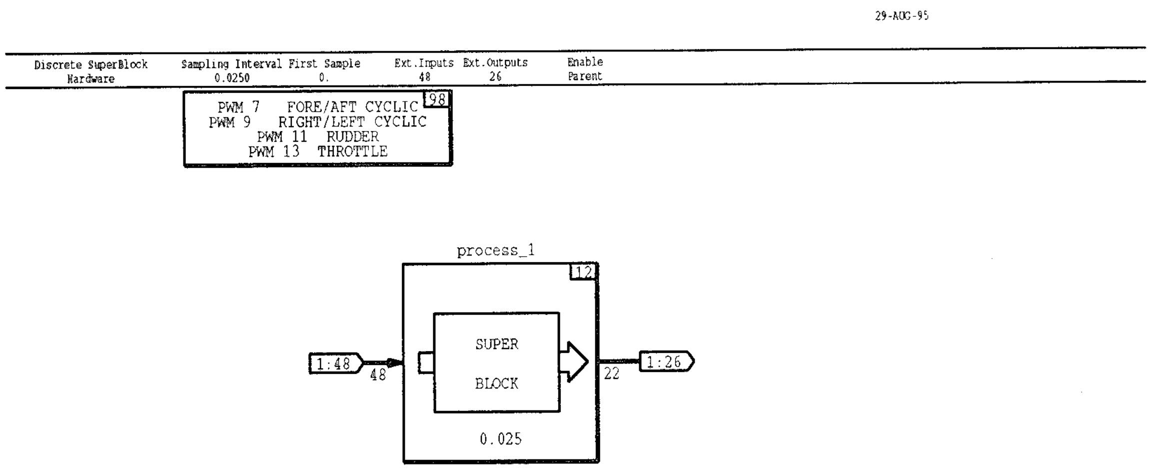


Figure B.1: 'Hardware' SuperBlock

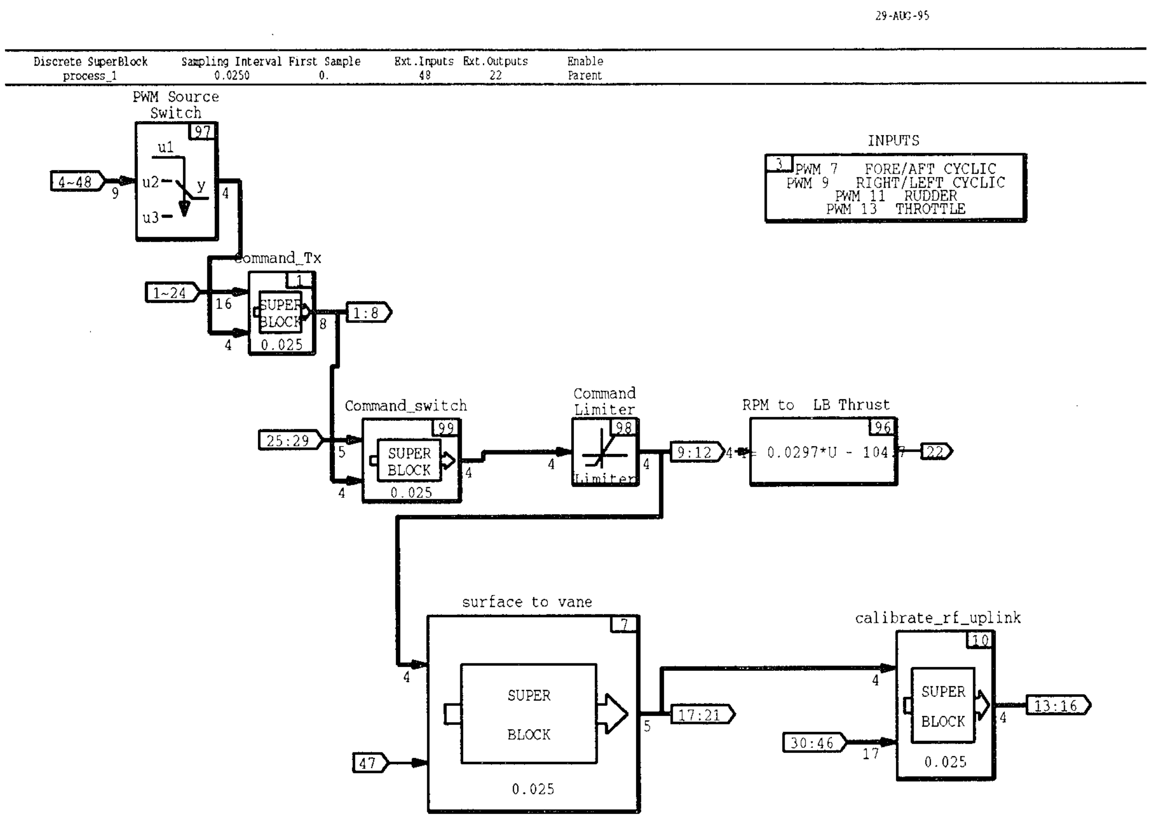


Figure B.2: 'Process 1' SuperBlock

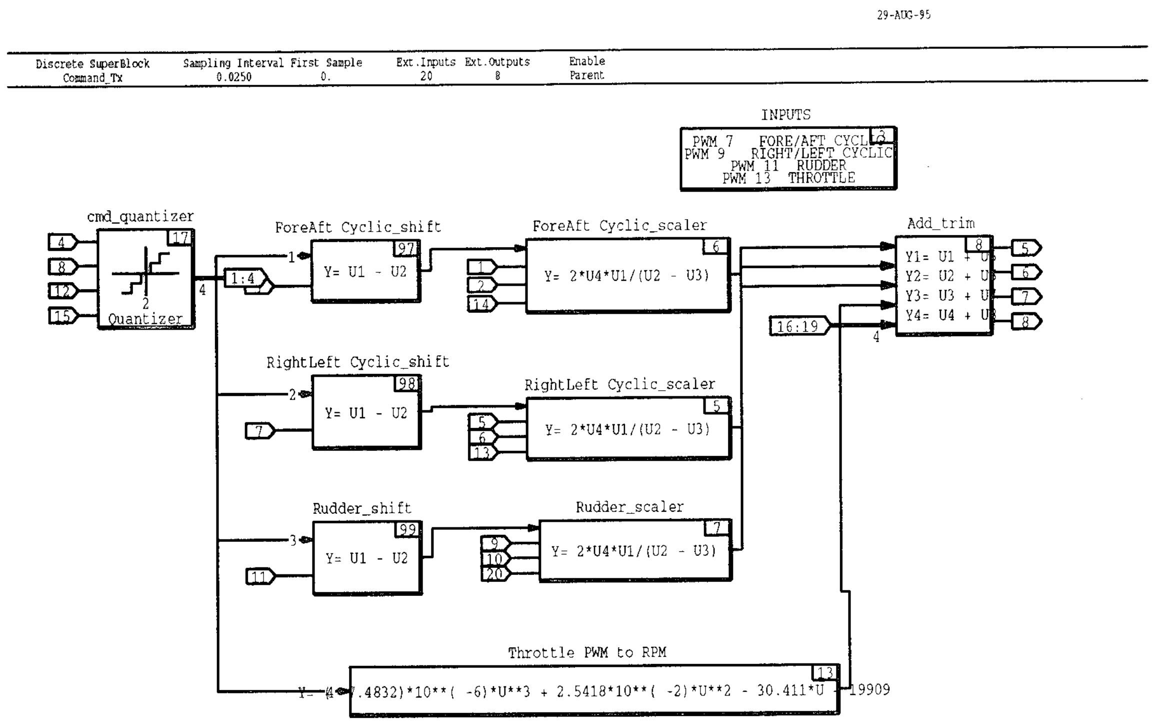


Figure B.3: 'Command Transmitter' SuperBlock

29-AUG-95

Discrete SuperBlock	Sampling Interval	First Sample	Ext.Inputs	Ext.Outputs	Enable
Command_switch	0.0250	0.	9	4	Parent

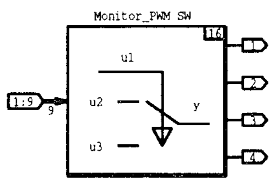


Figure B.4: 'Command Switch' SuperBlock

19-SEP-95

Discrete SuperBlock	Sampling Interval	First Sample	Ext.Inputs	Ext.Outputs	Enable
surface to vane	0.0250	0.	5	5	Parent

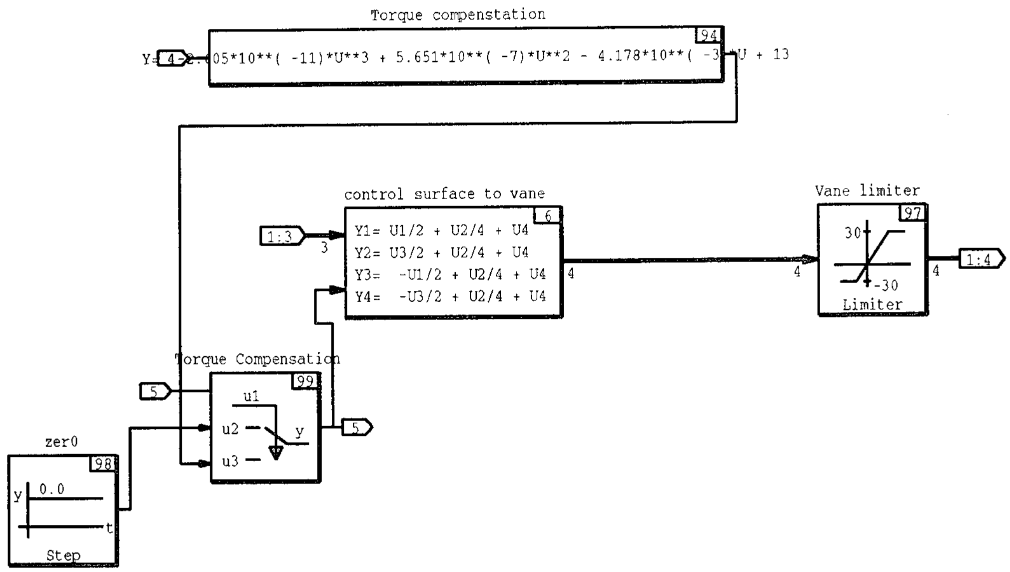


Figure B.5: 'Surface to vane' SuperBlock

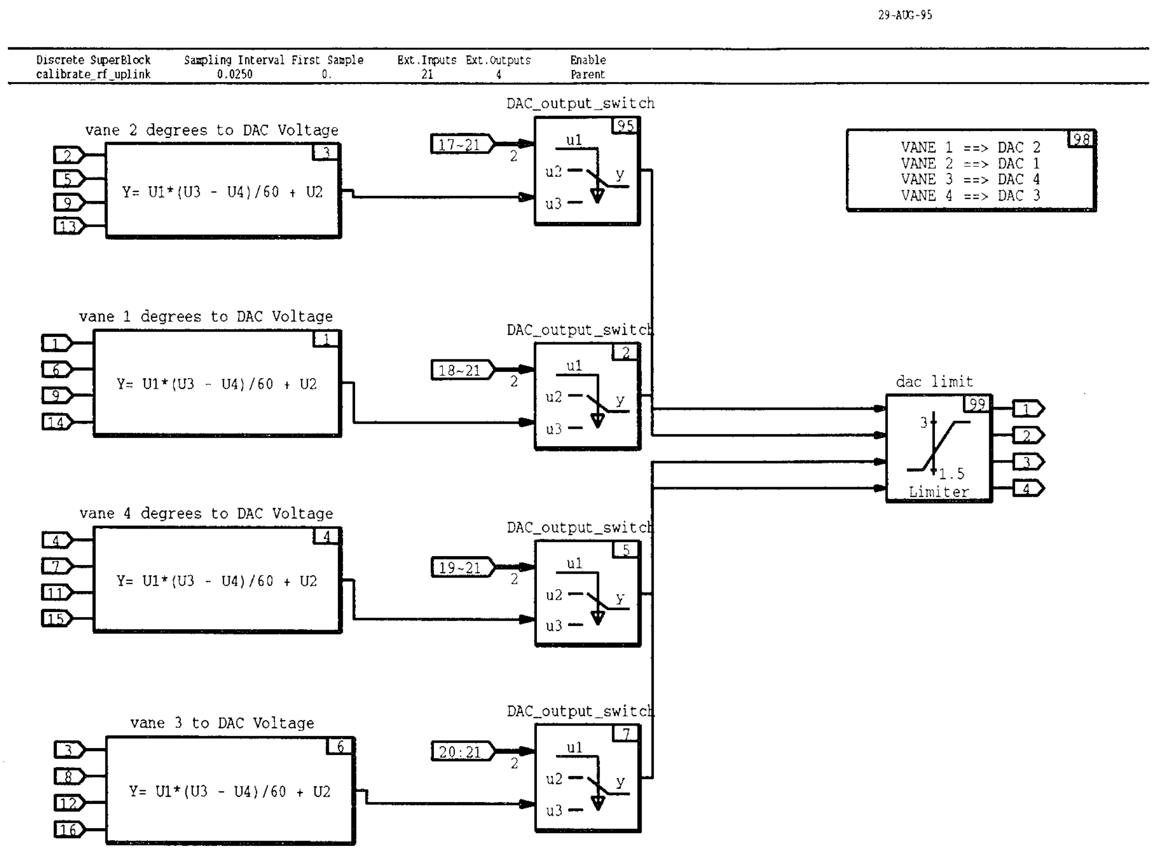


Figure B.6: 'Calibrate RF Uplink' SuperBlock

LIST OF REFERENCES

1. Moats, Michael L., *Automation of Hardware-in-the-Loop Testing of Control Systems for Unmanned Air Vehicles*, Master's Thesis, Department of Aeronautics and Astronautics, Naval Postgraduate School, Monterey, CA, September 1994.

2. Kataras, Dimitris., *Integration of an Inertial Naviagation Sensor Suite with An Unmanned Air Vehicle Flight Controller*, Master's Thesis, Department of Aeronautics and Astronautics, Naval Postgraduate School, Monterey, CA, March 1995.

3. Christofis, Alexandros, *On Design and Analysis of a Differential Global Positioning System (DPGS) Aided Navigation System for an Unmanned Airborne Vehicle*, Master's Thesis, Department of Aeronautics and Astronautics, Naval Postgraduate School, Monterey, CA, June 1995.

4. Sandia Laboratories, *AROD System Description*, December 1986.

5. Futaba Corporation of America, *Futaba Digital Proportional Radio Control Instruction Manual, PCM 1024 System*, January 1988.

6. Watson Industries, Inc., *IMU-600D Owner's Manual*, August 1993.

7. Hallberg, Eric N., *Design of a GPS Aided Guidance, Navigation, and Control System for Trajectory Control of an Air Vehicle*, Master's Thesis, Department of Aeronautics and Astronautics, Naval Postgraduate School, Monterey, CA, March 1994.

8. Kuechenmeister, David R., *A Non-Linear Simulation For An Autonomous Unmanned Airial Vehicle*, Master's Thesis, Department of Aeronautics and Astronautics, Naval Postgraduate School, Monterey, CA, September 1993.

9. Stoney, R. B., *Design, Fabrication, and Test of a Vertical Attitude Take-off and Landing Unmanned Air Vehicle*, Engineer's Thesis, Department of Aeronautics and Astronautics, Naval Postgraduate School, Monterey, CA, June 1993.

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